Using Joint Detection to Allow Safe Operation of Television Band “White Space” Devices*

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Abstract—The purpose of this study conducted by Shared Spectrum Company (SSC) was to determine a range of detection thresholds at which new dynamic spectrum access (DSA) devices can safely operate in unoccupied spectrum allocated to terrestrial television (TV) broadcasting and other services (i.e., the TV “white spaces”), without causing harmful interference. Spectrum sensing data were collected at six different locations in Northern Virginia that were strategically chosen because they are within, outside and near the edges of the predicted service contours of digital TV (DTV) stations serving the Washington, D.C. and Baltimore, MD metropolitan areas.

SSC engineers simulated a pair of DSA devices that would jointly decide if a channel can be used or not. This joint decision logic mitigates the propagation shadowing and hidden node problem. The DSA detectors used a high sensitivity detector that is able to detect the DTV pilot tone down to a −140 dBm level (DTV signal power level of −128 dBm). “Harm” is defined to be when the two DSA transceivers transmit within the DTV stations’ protected service contours. A keep-out distance of 10 km for higher powered (e.g., 10 W) DSA transmitters is also suggested, but not for low power (e.g., 100 mW) DSA systems. “False alarms” are defined as detections of distant DTV transmitters when the DSA system is located outside the DTV service contour(s) and outside the keep-out area.

Based on SSC’s analysis of data recorded at several independent locations in Northern Virginia and from 13 DTV stations, the following conclusions can be made:

1. **The Listen-Before-Talk, threshold-based approach is an effective dynamic spectrum access technique in the TV white spaces when joint detection is used.**
2. **A DSA system using a 10 W transmitter and sensing the DTV pilot threshold at -130 dBm (-118.5 dBm DTV signal power level) results in no or minimal harm and potentially acceptable false alarm rates.**
3. **A DSA system using a 100 mW transmitter and sensing the DTV pilot threshold of -120 dBm (-108.5 dBm DTV signal power level) would result in no harm and potentially acceptable false alarms rates.**

* A previous version of this paper was presented at the 3rd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks (Chicago, IL, Oct. 14-17, 2007).

I. Introduction

Shared Spectrum Company (SSC) has conducted a study to determine a range of detection thresholds at which new dynamic spectrum access (DSA) devices can safely operate in unoccupied spectrum allocated to terrestrial digital television (DTV) broadcasting and other services (i.e., the TV “white spaces”), without causing harmful interference. Spectrum sensing data were collected at six different locations in Northern Virginia that were strategically chosen because they were within, outside and near the edges of the protected “Grade B” service contours of DTV stations serving the Washington, D.C. and Baltimore, MD metropolitan areas.

This section identifies the key technical issues under consideration by the U.S. Federal Communications Commission (FCC) with regard to the use of spectrum sensing approaches that would ensure that new radio transmitting devices sharing the TV bands operate only on vacant frequencies without causing interference to broadcast television and other authorized services. We also summarize the findings of our study of the DTV signals in the Washington, DC/Baltimore, MD metropolitan area.

A. Key Technical Issues Considered by FCC

The FCC is considering rules for permitting new radio transmitting devices to share frequency bands currently allocated to the television broadcasting service and other services.[1] These TV white space devices would be authorized on frequencies that are not used by TV stations or other licensed services in each local area. The FCC is developing technical rules to govern the safe, interference-free operation of “personal/portable” devices and “fixed/access” operations on a licensed or unlicensed basis. The FCC has also been testing prototype white space devices.[2]

An important technical problem facing the FCC is how to ensure that TV white space devices operate only on vacant TV band frequencies without causing interference to television receivers and other authorized users. One of several methods being studied involves the authorization of new DSA devices that employ a “detect and avoid” or “listen before talk” strategy by which each device would utilize spectrum sensing

[1] *Notice of Proposed Rule Making* in ET Docket Nos. 02-380 and 04-186, 19 FCC Rcd 10018 (2004).

[2] Initial Evaluation of the Performance of Prototype TV-Band White Space Devices, *OET Report* FCC/OET 07-TR-1006, July 31, 2007; Evaluation of the Performance of Prototype TV-Band White Spaces Devices: Phase II, *OET Report* FCC/OET 08-TR-1005, Oct. 15, 2008).

techniques for detection of signals of DTV stations and other authorized transmitters. This would require each new device to have a spectrum scanning and sensing capability through which it would be able to process detected signals and determine which TV channels are occupied and which are vacant. Those channels deemed to be vacant could then be utilized by the DSA-enabled white space device consistent with the regulatory restrictions on transmissions in such frequencies. The FCC also suggested in its 2006 Further Notice of Proposed Rulemaking that a sensing approach could potentially be enhanced with geo-location via an embedded GPS receiver, database look-up, distributed sensing, and/or beacon identification techniques. [3]

The FCC is investigating whether and how to establish a detection threshold, which it defined as "the sensitivity level that would be used to determine the presence of other signals." In particular, it sought comment on whether such sensing capability should be able to detect signals as low as -116 dBm. It noted that the presence of signals above the threshold detection level would not necessarily exclude access to the spectrum, but would be a "gating factor" that is then followed by further processing to determine whether the spectrum can or cannot be used.

The FCC identified certain factors and considerations that must be taken into account in establishing an appropriate detection threshold. First, it was expected, that a DSA device operating in the TV band would likely be in close proximity to a TV receiver (*i.e.*, in the same or adjacent residence or business) and both would be relatively far from the TV transmitter. In this scenario, the TV receiver would be attempting to receive a relatively weak TV signal in the presence of a relatively strong signal from the DSA device. The height of the white space device's transmitting antenna also would affect the potential interference distance.

Second, the FCC stated that the increased potential for "false positives" or "false alarms" must be taken into account in cases where a detection threshold that is too low results in increased false positives in response to detecting spurious radio noise or other white space devices, sharply reducing the usefulness of this spectrum for such devices.

Third, the FCC was also concerned about relying solely on a detection threshold as the gating criteria for access to the white spaces spectrum and whether this approach, by itself, would be effective in preventing harmful interference to TV stations within their protected contours due to the problem of the "hidden node" (*i.e.*, where an obstruction between the sensing receiver and the signal to be detected causes a failed detection of an occupied channel).

As an alternative to decreasing the detection threshold, which would increase the possibility of false detections and result in other detrimental effects on the device's cost and performance, the FCC, citing SSC's reply comments, suggested the use of distributed sensing. Distributed sensing or "group behavior" approaches utilize multiple antennas and sensing receivers at different locations that share channel availability information with each other. As the FCC noted, "when multiple receivers that share information are used, the probability of missing a signal may be greatly reduced because only one receiver needs to detect a signal to ascertain that a particular channel is occupied, and the likelihood would seem low that every receiver in a system would be obstructed from receiving a signal."

SSC's study of a joint detection approach affirms the FCC's tentative conclusion about the effectiveness of distributed sensing even in the case where only two DSA-enabled white space nodes are deployed.

B. *Summary of SSC's Findings*

The goal of SSC's analysis was to determine bounds on the values of detection thresholds at which DSA devices can safely operate in the TV bands, without causing interference to primary users. We used a pair of DSA devices that jointly decided if a TV channel can be used or not. This emulated how SSC's and other DSA devices operate. The joint decision logic mitigates the propagation shadowing and hidden node problem. The separation between the DSA devices was less than 10 km to correspond to the link range of a 10 W 802.16-based transceiver developed by SSC.

SSC used a high sensitivity detector that is able to detect the DTV pilot tone down to -140 dBm, which translates to a total DTV received signal power level of -128 dBm. "Harm" is defined to be when the two DSA transceivers transmit within the DTV stations' protected service contours. A keep-out distance of 10 km for higher powered (*e.g.*, 10 W) DSA transmitters is also suggested, but not for low power (*e.g.*, 100 mW) DSA systems. "False alarms" are defined as detections of distant DTV transmitters when the DSA system is located outside the DTV service contour(s) and outside the keep-out area.

Based on SSC's analysis of data recorded at several independent locations in Northern Virginia and from 13 DTV stations, the following conclusions can be made:

- The Listen-Before-Talk, threshold-based approach is an effective dynamic spectrum access technique in the TV white spaces when joint detection is used.
- A DSA system using a 10 W transmitter and sensing the DTV pilot threshold at -130 dBm (-118.5 dBm DTV signal power level) results in no or minimal harm and potentially acceptable false alarm rates.
- A DSA system using a 100 mW transmitter and sensing the DTV pilot threshold of -120 dBm (-108.5 dBm DTV signal power level) would result in no harm and potentially acceptable false alarms rates.

The false alarm rate caused by detection of distant TV transmitters when the DSA device was located outside of the service contour was still significant (20-40 percent using the above threshold values), but this would be acceptable if sufficient bandwidth is available in other open channels.

[3] *First Report and Order and Further Notice of Proposed Rule Making* in ET Docket Nos. 02-380 and 04-186, FCC 06-156 (rel. Oct. 18, 2004), 71 Fed. Reg. 66897 (Nov. 17, 2006).

In the following sections we describe the equipment used in the tests, describe the test locations, identify the TV channels analyzed, summarize the measured data, explain the detection threshold analysis metrics and results, and provide our conclusions.

II. Equipment Description

This section describes the equipment used in the tests.

A. *RF Chain Description*

Fig. 1 shows the sensor equipment used at each of the collection sites. An omni-directional discone antenna was used to receive ambient signals at each sensor location. The antenna had a height of 1.5 meters indoors and 2.87 meters outdoors.

A pre-selector was used to maintain a low noise figure while rejecting strong out of band signals. The pre-selector block diagram is given in Fig. 2. The pre-selector allowed remote automated selection of antennas, filters, amplifiers and attenuators. Only the upper pre-selector portion with a single antenna was used in these measurements (30 MHz to 1 GHz).

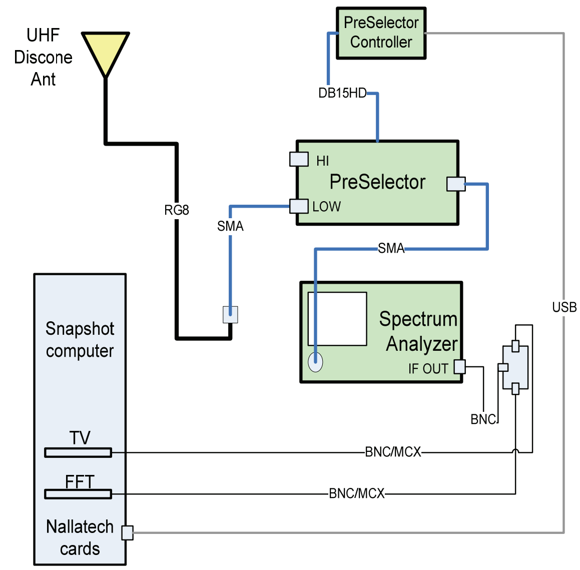

Figure 1. Signal Collection Equipment Block Diagram

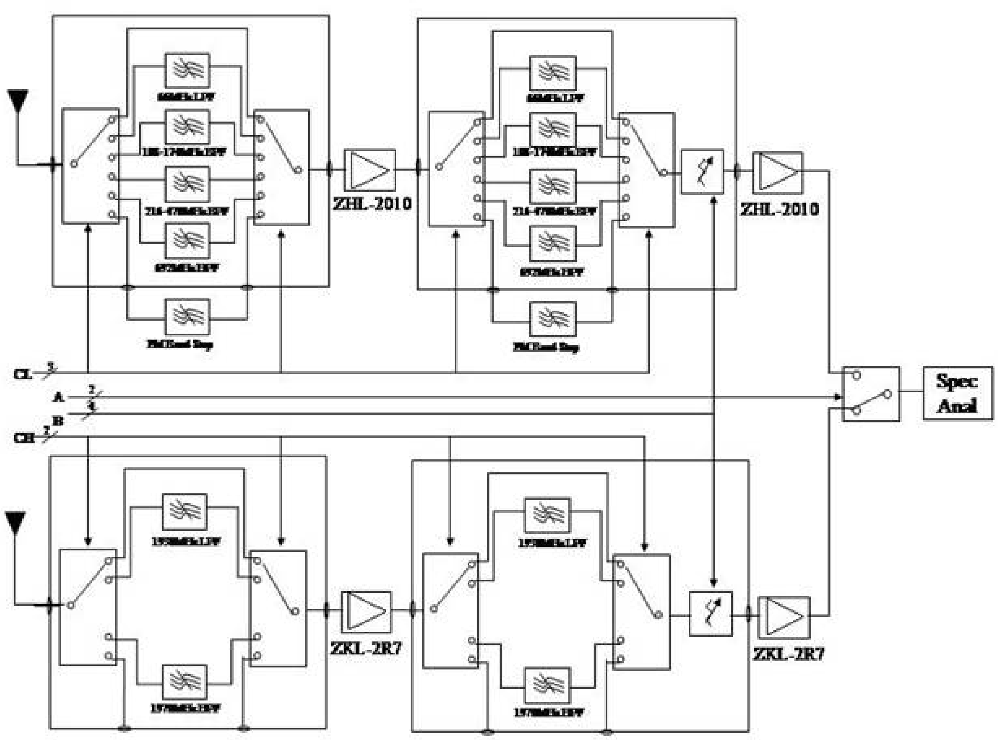

Figure 2. Pre-Selector Diagram

The signal was then fed into a spectrum analyzer, followed by a sampler and an embedded processor. RF from the antenna was converted to an intermediate frequency and then digitized and saved to a file. The data in the file was then analyzed and plotted. Refer to signal path in Fig. 3.

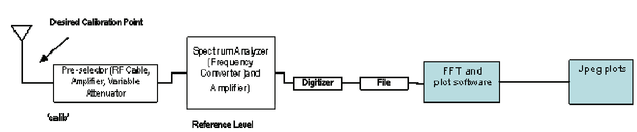

Figure 3. RF Signal Chain

B. Digital Signal Processing Description

The detector processor received a down-converted RF signal at a 20.4 MHz IF, using a spectrum analyzer. This 20.4 MHz IF was sampled at 58.5 Mega-samples/second and digitized at 14 bits of accuracy. Within a Virtex FPGA the signal was filtered and down-converted to baseband. Refer to Fig. 4. The FPGA processor generated 90 thousand complex samples per second. The detector's processor performed a FFT on data sampled about 45 kHz either side of a centered DTV carrier frequency for each of the DTV channels.

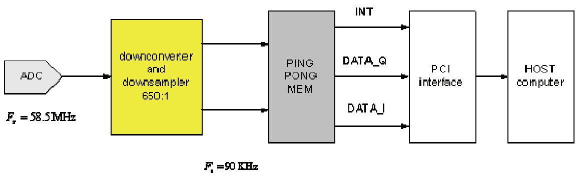

Figure 4. DTV Detector Signal Processing

All measured powers were referenced to the antenna. Prior to calculating the received power the gain of each stage of electronics was measured across the frequency range. The RF signal path was calibrated over all frequencies and pre-selector configurations. The configuration below used a test tone at -100 dBm to calibrate the digitizer. Refer to Fig. 5.

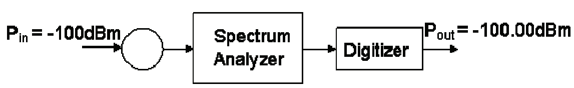

Figure 5. Calibration

Each sensor system was time synchronized to the time of a GPS receiver. In this way each sensor was receiving the same DTV channel at the same time within 10 ms. A computer was used to serially step through DTV channels by controlling the center frequency of the pre-selector and spectrum analyzer. The data was collected, processed and stored to binary data files.

C. ATSC DTV Pilot Power Detector Description

This section provides a high-level overview of the ATSC DTV Pilot Power Detector used in the tests.

1) Detector Summary

The ATSC DTV signal pilot tone distinguishes the digital TV signal and enables it to be easily detected. It is narrowband and uses the same frequency all the time. Thus, it is much easier to monitor the power received on the pilot frequency only to detect the presence or absence of the TV signal instead of detecting a 6 MHz wide signal.

2) NTSC/DTV Signal Overlap - Offset

If nearby NTSC stations are operating on the same or adjacent channels as DTV stations, DTV stations sometimes use frequency offsets. For the channels observed in this study, no nearby NTSC signal co-existed and, hence, DTV pilot offsets were not employed by these stations. If DTV offset piot tones were used, a simple change in the detector software would have been implemented.

3) Pilot Signal Power Level Compared to Total Signal Power Level

The DTV ATSC pilot contributes 0.3 dB to the total signal power. Thus, the difference between the measured carrier power level is 10*log10(1-10^0.03) = -11.45 dB. For example, if a pilot measured at -100 dBm the signal power is -88.55 dBm. In general, the DTV pilot tone signal power is not directly related to the total DTV signal power at any instant because of multi-path propagation effects. These narrow bandwidth signals are attenuated by time variable multi-path with a period of 2 to 10 minutes.

SSC's approach used the maximum measured pilot tone amplitude over a 2 to 10 minute period, and then add the 11.5 dB correction factor to estimate the total received TV power value. This provides a conservative, upper limit on the total received TV power value.

D. Joint Detection Algorithm

Sensors were paired as indoor and outdoor nodes and they synchronously collected data, but they did not during these tests actually communicate with each other. When the pilot power was examined, the information from the outdoor and indoor nodes was combined to make the detection determination and simulate the transmission decision. The probability of successful detection was enhanced by considering a union of the probabilities of detection by each sensor. This ensured that if one sensor was affected by a shadowed node issue, by a building blockage or local propagation loss, the other sensor was able to compensate for the loss, by providing the most accurate picture. For each time instant, the pilot power values from both sensors were compared and if one crossed the detection threshold, a detection was considered to be made.

The advantage of using both indoor and outdoor sensors is one of robustness. If there are situations where a multi-path null obscures the signal to one sensor, it is likely that the second sensor will pick up the signal. If the indoor sensor sees a signal or the outdoor sensor sees the signal, the information would be conveyed to all participant DSA devices, and all will then quickly vacate the channel to avoid causing interference.

III. Test Locations and TV Channels Used

This section describes the test locations and the TV channels used in the tests and analysis.

A. Test Locations

The tests were designed to collect and sense the DTV signal at multiple locations using a base station (outdoor antenna) and customer device (indoor antenna). The locations were chosen to cover regions inside, outside and on the boundary of DTV stations' service contours. These tests were performed in the Northern Virginia area within the Washington, DC metropolitan region.

Table I shows the indoor node and the outdoor nodes' latitude and longitude values, and the separation between the nodes. The separations were selected to be consistent with a 10 W link distance.

TABLE I. TEST LOCATION COORDINATES AND SEPARATION BETWEEN NODES

Location	Indoor Node Latitude (deg)	Indoor Node Longitude (deg)	Outdoor Node Latitude (deg)	Outdoor Node Longitude (deg)	Indoor-Outdoor Separation (km)
Vienna	38.9268	77.2463	38.9	77.22	3.75
Manassas	38.7882	77.448	38.7712	77.4522	1.92
Ashburn	39.02	77.43	39.05	77.48	5.46
Dale City	38.602	77.2918	38.6343	77.3512	6.29
Luray	38.68	78.42	38.7	78.44	2.82
Gainesville	38.86	77.78	38.88	77.61	14.88

Fig. 6 shows a map with the test locations.

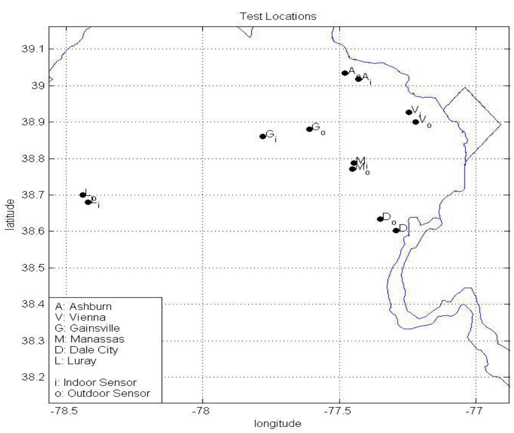

Figure 6. Measurement Locations

Fig. 7 shows the indoor equipment inside a hotel room in Manassas, VA. The discone receiving antenna was mounted on a stand inside the room.

Figure 7. Measurement equipment located in the Indoor Manassas, VA location.

Fig. 8 is a photograph that shows the equipment installed in a van at the outdoor Manassas, VA location. The discone receiving antenna was mounted on top of the van.

Figure 8. Measurement equipment located in van at the Outdoor Manassas, VA location.

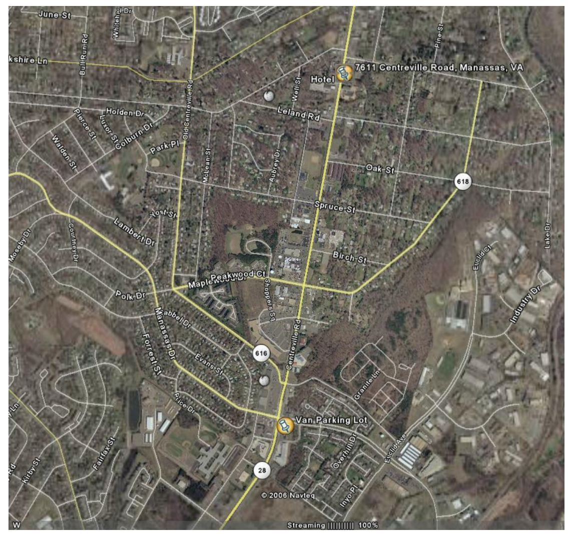

Figure 9. Map showing location of Manassas, VA Test Locations

B. DTV Channels in the Test Area

DTV channels from 2 to 51 were investigated for identifying available white space.[4] Data was collected for these channels during each experiment.

Table II shows the list of DTV channels in this area with an ERP higher than 500 kW based on FCC data. A 2.4º by 2º region between lower left corner at 37.9 N, -78.7 W and upper right corner at 39.9 N, -76.3 W (approximately 36343 square kilometer area centered on the test locations) was considered as the area of influence for this analysis. These channels were used in the analysis described in later sections. At the time of the tests, channel 38's licensed ERP was 1000 kW, but it transmitted at 306 kW. Channel 40's licensed ERP was 845 kW, but it transmitted at 9.2 kW during our tests.

[4] Channels 52 – 69 were excluded as those channels have been reallocated for new commercial and public safety services.

TABLE II. AREA DTV STATIONS

Channel No.	Call Sign	ERP (kW)	HAAT (m)	Latitude	Longitude	City, State
21	WBOC-TV	635	279	N 38 30 17.0	W 75 38 37.0	Salisbury, MD
23	WLYH-TV	500	381	N 40 15 45.0	W 76 27 51.0	Lancaster, PA
24	WATM-TV	1000	311	N 40 34 06.0	W 78 26 38.0	Altoona, PA
30	WGCB-TV	500	174.2	N 39 54 18.0	W 76 35 00.0	Red Lion, PA
32	WTAJ-TV	883	305.2	N 40 34 01.0	W 78 26 30.0	Altoona, PA
34	WUSA	1000	254	N 38 57 01.0	W 77 04 47.0	Washington DC
36	WTTG	1000	201	N 38 57 22.0	W 77 04 59.0	Washington DC
38	WJZ-TV	306	312	N 39 25 05.0	W 76 39 03.0	Baltimore, MD
39	WJLA-TV	646	254	N 38 57 01.0	W 77 04 47.0	Washington DC
40	WNUV	9.2	372.8	N 39 20 10.0	W 76 38 59.0	Baltimore, MD
47	WPMT	933	385	N 40 01 41.0	W 76 36 00.0	York, PA
47	WUPV	1000	249	N 37 44 31.0	W 77 15 15.0	Ashland, VA
48	WRC-TV	813	242	N 38 56 24.0	W 77 04 54.0	Washington DC

Table III shows the distance and bearing of the test locations to the location of the DTV stations in the area.

TABLE III. DISTANCE AND BEARING OF TEST LOCATIONS TO THE SELECTED DTV STATIONS

	Gainesville		***Vienna***		***Ashburn***		***Dale City***		***Manassas***	
Ch#	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**	**Dist (km)**	**Bear.**
21	182.64	347.80	145.23	342.27	167.42	340.31	146.44	355.59	159.84	349.54
23	187.38	416.12	163.86	426.52	161.56	418.63	197.11	428.34	185.30	423.16
24	199.41	108.49	211.12	118.97	191.16	115.90	237.21	113.56	216.31	112.84
30	149.59	410.65	123.60	423.34	123.10	412.83	156.58	426.28	145.65	419.49
32	199.20	108.45	210.90	118.94	190.94	115.87	236.99	113.53	216.09	112.81
34	54.01	369.72	13.92	377.23	33.53	345.58	42.48	420.49	37.26	390.73
36	53.83	370.45	13.85	380.15	33.10	346.54	42.90	421.26	37.35	391.81
38	251.95	294.91	242.63	285.54	260.30	289.00	213.67	289.93	234.40	291.07
39	54.01	369.72	13.92	377.23	33.53	345.58	42.48	420.49	37.26	390.73
40	104.05	390.21	68.89	403.22	77.52	386.66	98.73	414.18	92.76	402.09
47	159.46	414.21	135.35	426.52	133.40	416.91	168.62	428.63	156.86	422.52
47	131.19	287.20	130.26	269.20	143.85	277.06	97.59	273.49	116.64	278.50
48	53.67	368.54	13.46	372.79	33.68	343.62	41.40	419.91	36.55	389.32

C. Test Locations Relative to DTV Transmitter Service Contours

In this study, harmful interference was assumed if the test location was inside the DTV station's Grade B signal contour and the DSA device would make a decision to transmit on the station's channel. (If the rules also restrict DSA transmissions on adjacent channels in certain circumstances, the same detection determination would inform the decision to transmit, and at what power, in adjacent frequencies as well.) Harm (as defined below) to television receivers was assumed to have been caused even if received signal strength was less than -84 dBm (threshold of visibility for DTV signals. In situations where a higher power DSA transmitter (*e.g.*, 10 W) would be used and the test location was still within a keep-out distance (defined below) surrounding the protected contour, if the DSA device would have decided to transmit harm was also assumed. Otherwise, signal detection that would lead to no transmission was treated as a false alarm (as defined below).

Fig. 10 shows the test locations and the DTV stations' service contours. Test locations were inside, outside or near the border of the predicted/protected service contours. The contour data was downloaded from the FCC database.[5] Channels 38 and 40, however, were operating at less than full power at the time of the experiments. Therefore, using the full power contour was not appropriate. We used proportionality arguments to estimate the real reduced power contour distance. Using the FCC propagation modeling tool[6] the expected full power contour distance and the reduced power reduced power contour distance were found.

The color coded triangles in Fig. 10 indicate the DTV transmitter locations for the respective stations. The test locations are shown with black circles. At each location, two sensors were used, one indoor (inside a building) and one outdoor. The information was integrated from the two sensors to arrive at a detection/transmission decision. The suffix "o" denotes an outdoor sensor and the suffix "i" denotes an indoor sensor.

[5] http://www.fcc.gov/ftp/Bureaus/MB/Databases/fm_tv_service_areas/service_contour_data/readme.html
[6] http://www.fcc.gov/mb/video/tvq.html

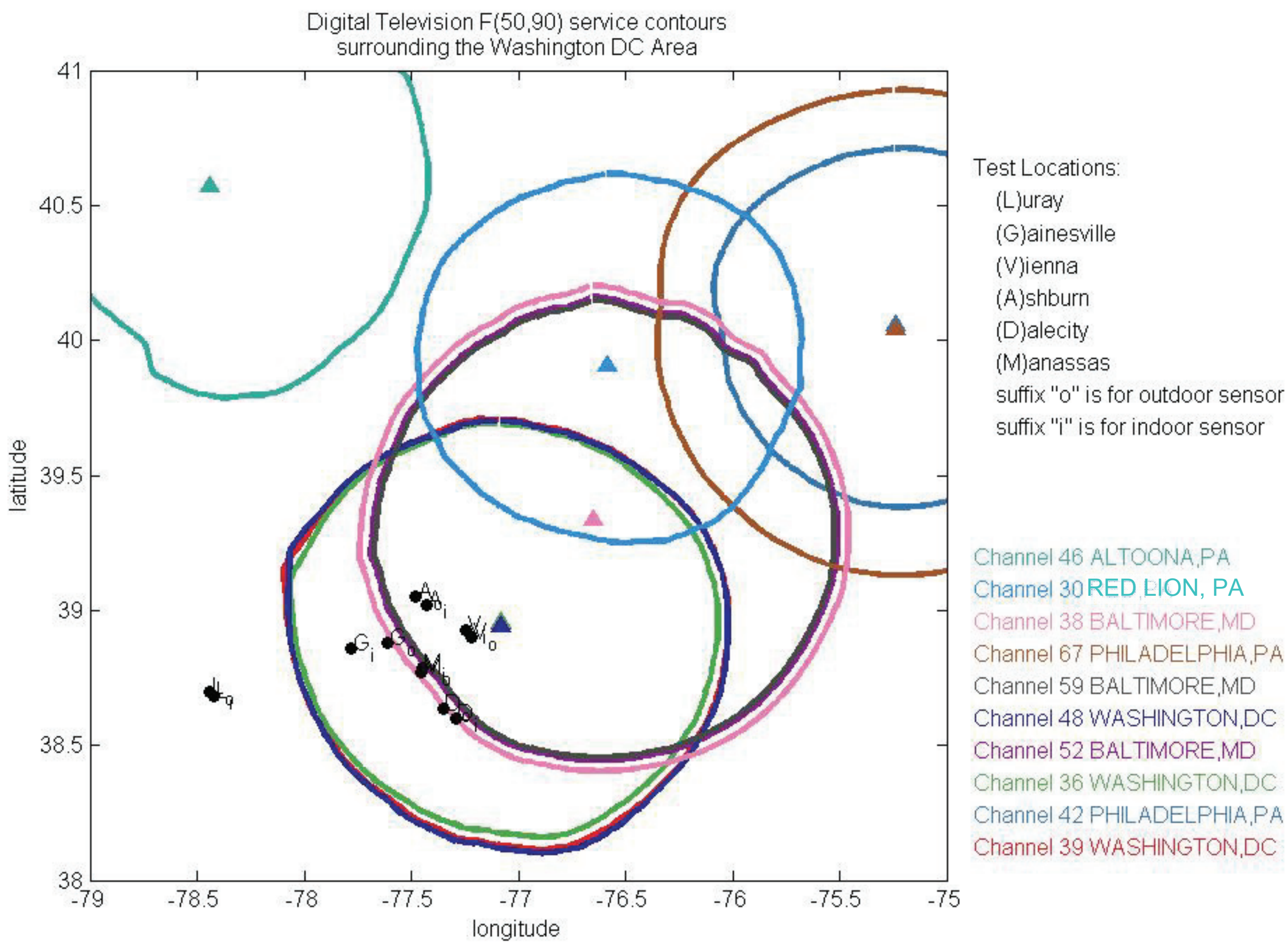

Figure 10. F(50, 90) DTV Service Contours

Table IV lists the test locations and their categorization as either inside or outside of the DTV Station service contours.

TABLE IV. CATEGORIZATION OF TEST LOCATIONS AS EITHER INSIDE OR OUTSIDE THE SERVICE CONTOUR OF THE ACTIVE AREA TV CHANNELS

	Area Channels												
City	**21**	**23**	**24**	**30**	**32**	**34**	**36**	**38**	**39**	**40**	**47**	**47**	**48**
Vienna	0	0	0	0	0	1	1	1	1	1	0	0	1
Manassas	0	0	0	0	0	1	1	1	1	1	0	0	1
Ashburn	0	0	0	0	0	1	1	1	1	1	0	0	1
Dale City	0	0	0	0	0	1	1	1	1	1	0	0	1
Luray	0	0	0	0	0	1	0	0	0	0	0	0	0
Gainesville	0	0	0	0	0	1	1	0	1	0	0	0	1
Channel categories		0: Outside the contour 1: Inside the contour											

D. Measurement Duration

The measurements at each location lasted approximately 24 hours. This enabled us to account for propagation variations such as fading, ducting and aircraft reflections.

IV. EXAMPLE MEASURED DATA

This section describes some example measured data.

A. Measured Times Series

Fig. 11 shows DTV signal pilot power versus time for channel 39 at the Dale City test location. There is significant carrier power level variation with time. For example, the peak at about the 375th minute of the experiment was missed by the indoor sensor, but owing to data from the outdoor sensor, a successful detection was made. The difference in sensor estimates in this case is negligible due to the fact that the Dale City test location is well inside the contour boundary of channel 39.

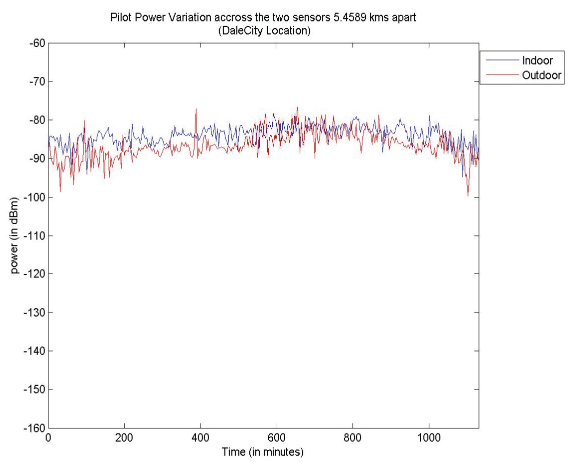

Figure 11. Pilot power Variability with Time for Channel 39 at the Dale City Test Location

B. Power Levels at Indoor/Outdoor Locations

In general, where the outdoor test locations were open areas like a camp ground, the correspondence between power levels of the indoor and outdoor pilot power was much higher than in the cases where the outdoor locations were in areas with buildings like a car dealership or a residential parking garage. This suggests significant propagation losses as a result of building blockage of up to a 30 dB difference as shown in Fig. 12.

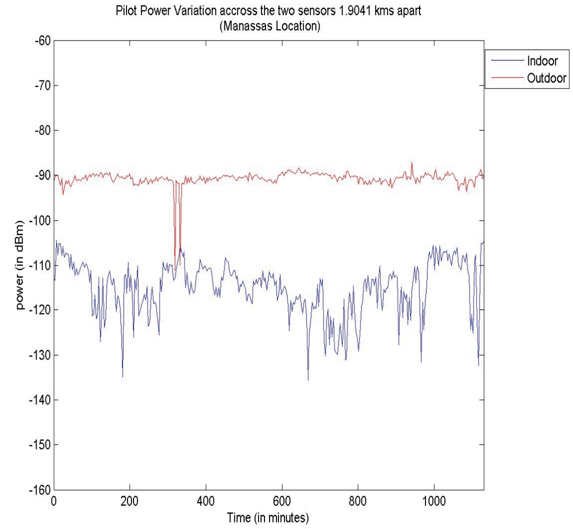

Figure 12. Pilot power Variability with Time for Channel 36 at the Manassas Test Location

V. TV WHITE SPACE THRESHOLD ANALYSIS

The analysis goal was to determine the upper and lower bounds on the detection threshold to be used with DTV pilot power measurements for safe operation of DSA devices that guaranteed no harmful interference.

A. Keep-Out Distance

A "keep-out distance" was established based on calculations made using the FCC's TV Query model estimates to provide an extra measure of protection to primary users and to test detection reliability within the area surrounding the protected contour. At an ERP value of 10 Watts (which was the assumed maximum power a DSA device was expected to use, especially in rural areas) and the antenna height of 30 meters, the field strength would go to 40 dBu at a distance of 9.406 km. 41 dBu was the value used to define F(50,90) contour limits. Thus, a 10 km keep-out distance was established for purpose of this analysis. For a 100 mW transmitter, no keep-out distance was deemed necessary.

B. Analysis Metrics

Two metrics used to assess the performance of the joint detection approach are defined in this section: Harm and False Alarms.

Harm. A conservative approach was used to define the harm causing conditions. When the DSA device was inside the service contour and the keep-out distance (where applicable) for a given DTV channel, the expectation was that it should always be able to detect the DTV signal on that channel and stay off that channel. Thus, if the sensor did not detect the TV signal inside the contour plus the keep-out distance, then, this was defined as a harm condition. When a high power DSA device was outside the service contour for a given TV channel, but still within the keep-out distance limits, we continued to flag this as harm if the high power DSA device decided to transmit. Thus, in this case, the required detection area was conservatively defined as the FCC-defined contour plus the keep-out distance. Accordingly, a high power DSA device would be permitted to transmit only when it was well outside the service contour of a given TV station. With this strategy, the DSA device would often make an overly cautious decision (so as not to cause harm) as the received DTV signal may possibly be too low for over-the-air reception by television receivers.

False Alarm. When a DSA device's sensor was outside the service contour plus the keep-out distance for a given DTV channel, the expectation was that there should be no TV signals for the DSA radio to detect and, thus, would be able to transmit. If the DSA sensor did detect a TV signal outside the contour plus the keep-out distance, then it was determined to be a false alarm. However, full power TV signals do not arbitrarily stop at the contour edge and sometimes a good TV signal is received at locations well outside of the protected contour. We assumed that television receivers outside the DTV station's contour plus the keep-out distance would not protected, but we also assumed that they would only be receiving DTV signals under favorable terrain conditions and extraordinary antenna heights. Thus, we flagged as false alarms the cases where the pair of DSA devices decided not to transmit when they were outside the contour boundary and the keep-out distance, and when the received TV signal was lower than -84 dBm (TOV).

C. Detection Threshold Selection

If the detection threshold is continually raised, then at a point it would not be able to sense the protected TV signal, even a strong TV signal. Therefore, with an increasing detection threshold the rate of harm will go to 100 percent. If the detection threshold is continually lowered, then at a point it will begin to sense the noise floor. Therefore, with a decreasing detection threshold the rate of false alarms will go to 100 percent. Clearly, as the FCC pointed out, while a very low detection threshold will ensure "no harm", it will also raise the false alarm rate so high that the DSA radio would never be able to transmit and would be of no practical use.

Fig. 13 shows the change of the probability of harm (assuming a 10 km keep-out distance corresponding to a 10 W DSA transmitter) and false alarm versus the DTV pilot power detection threshold. The DTV signal power level is 11.45 dB above the DTV pilot power level. This data includes the six locations across twelve DTV TV channels in and around the Washington, D.C. area. An upright red bar indicates the harm rate and an inverted blue bar indicates the false alarm rate. These results show that a pilot threshold of -130 dBm (-118.5 dBm DTV power level) would result in no or minimal harm and a potentially acceptable false alarm rate. We note, however, that the false alarm rate caused by detection of distant TV transmitters when the DSA device was located outside of the service contour and the keep-out distance was still significant (20-40 percent using the above threshold values), but this would potentially be acceptable if sufficient bandwidth is available in other open channels.

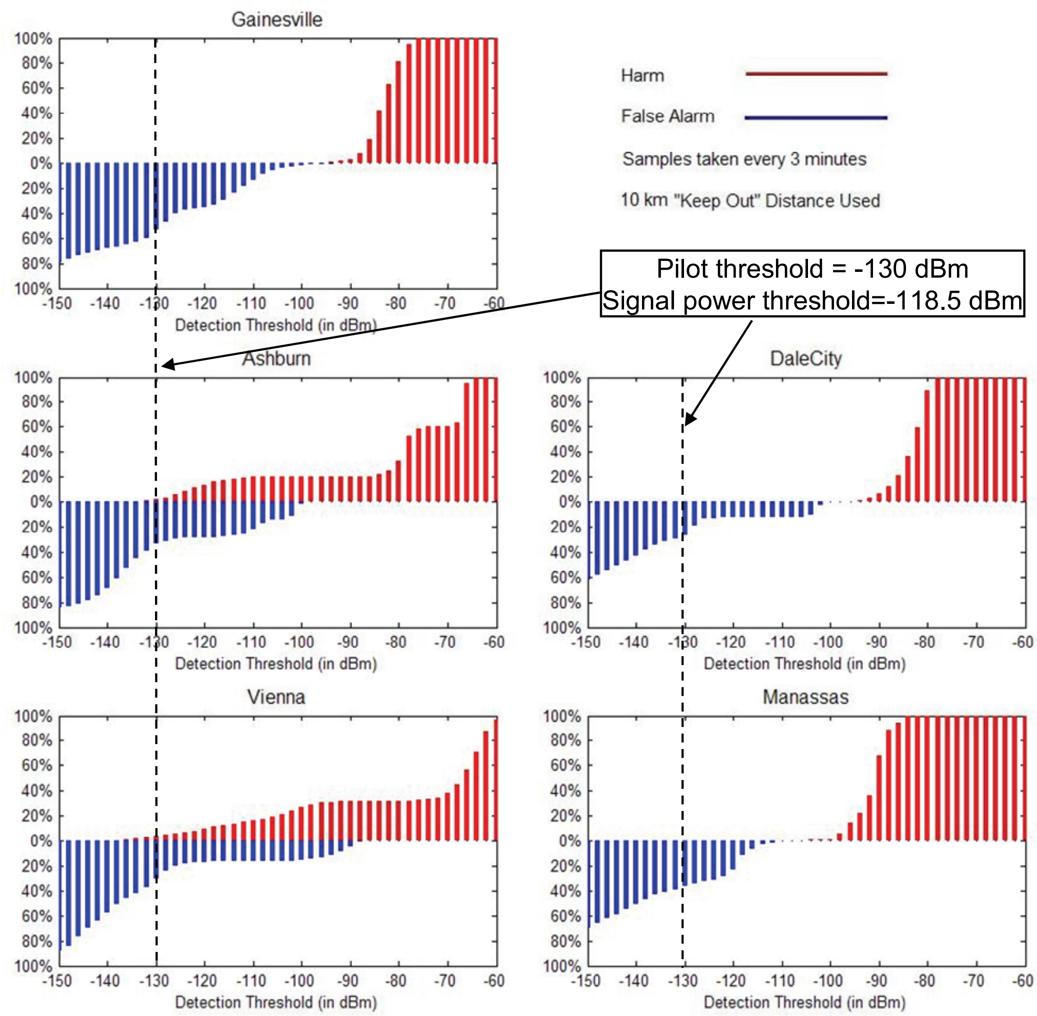

Figure 13. Probability of harm and false alarm versus detection threshold (10 km keep-out distance corresponding to a 10 W DSA transmitter).

Fig. 14 shows the change of the probability of harm (assuming no keep-out distance corresponding to a 100 mW DSA transmitter) and false alarm versus the DTV pilot power detection threshold. The DTV signal power level is 11.45 dB above the DTV pilot power level. This data includes the six locations across twelve DTV TV channels in and around the Washington, D.C. area. An upright red bar indicates the harm rate and an inverted blue bar indicates the false alarm rate. These results show that a pilot threshold of -120 dBm (-108.5 dBm DTV power level) would result in no harm and an acceptable false alarm rate.

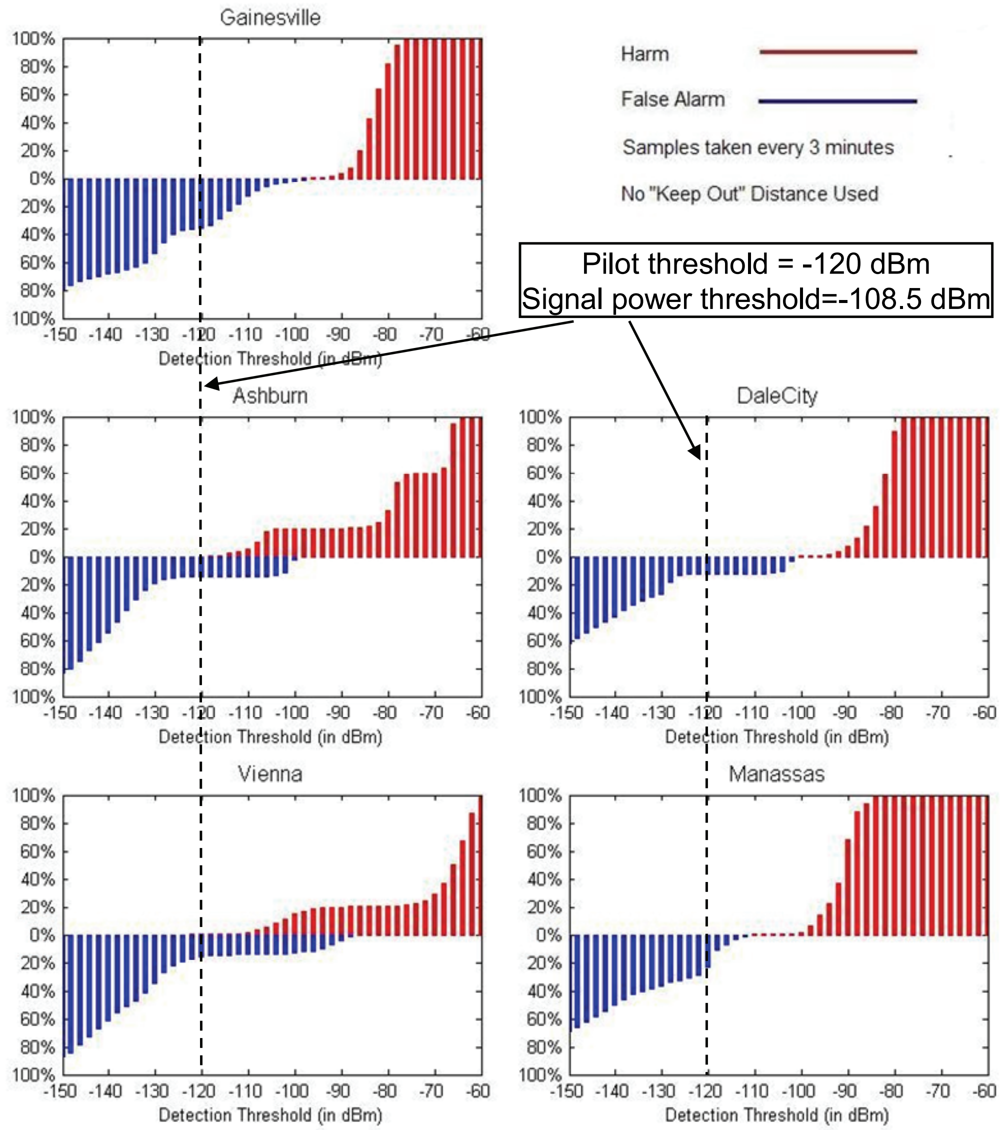

Figure 14. Probability of harm and false alarm versus detection threshold (no keep-out distance corresponding to a low power, 100 mW transmitter).

VI. Conclusion

It is important that the FCC's technical rules for TV white space devices ensure they operate only on vacant TV band frequencies without causing interference to broadcast television and other authorized services. New devices employing dynamic spectrum access (DSA) techniques such as "detect and avoid" or "listen before talk" strategies must have spectrum scanning and sensing capabilities that can reliably process detected signals and determine which TV channels are occupied and which are vacant.

Such rules may establish a detection threshold or sensitivity level that would be used as a "gating factor" that would inform the DSA devices' decisions to use a particular channel, but the FCC was rightly concerned about relying solely on a detection threshold as the gating criteria for access to the white spaces spectrum. To prevent harmful interference to TV stations within their protected contours, avoid the "hidden node" problem, and minimize false alarms, we have shown that a simple joint detection approach can work effectively at reasonable detection thresholds that can vary depending on the DSA devices' output power.

Our analysis shows that the values of detection thresholds can be established based on a pair of DSA devices that would jointly decide if a TV channel can be used or not. The joint decision logic effectively mitigates the propagation shadowing and hidden node problems.

Accordingly, if a DSA system uses a 10 W transmitter, then an DTV pilot detection threshold of -130 dBm (-118.5 dBm DTV power level) would result in no or minimal interference to protected DTV receivers and a potentially acceptable false alarm rate. A 10 km keep-out distance surrounding the DTV stations' protected Grade B contour is suggested for higher power DSA systems to further mitigate the likelihood of harm. If a DSA system uses a 100 mW transmitter, then an DTV pilot threshold of -120 dBm (-108.5 dBm DTV power level) would result in no harmful interference and an acceptable false alarm rate.